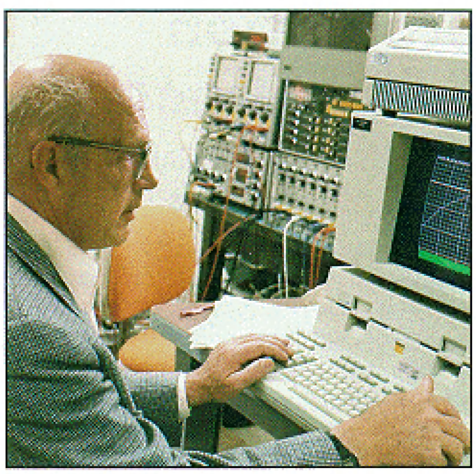
Bently's Corner

Fluid average circumferential velocity ratio a key factor in the rotor/bearing/seal models

It is well known that circumferential flow in bearings and seals (as well as in the main flow of fluid-handling machines) is responsible for creating conditions of rotor instabilities, known as oil whirl/whip, steam whip, etc.

Recent laboratory and analytical research has yielded an adequate model of fluid dynamic forces which is not only easy to handle in rotor dynamic analyses, but brings direct and clear interpretation of physical phenomena occurring in bearings and seals and provides tools for rotor instability control.



By Donald E. Bently
Chief Executive Officer, Bently Nevada Corporation
President, Bently Rotor Dynamics Research Corporation

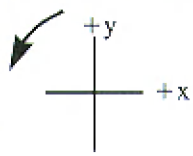
In the classical rotor/bearing/seal models, the fluid dynamic forces are taken into consideration through the bearing and/or seal coefficients. The coefficients responsible for rotor instabilities are mainly these in the stiffness matrix:

$$\begin{bmatrix} k_{xx} & k_{xy} \\ -k_{yx} & k_{yy} \end{bmatrix} \qquad (1)$$

Using only stiffness coefficients, the fluid film force components in the x (horizontal) and y (vertical) directions for a counterclockwise rotating shaft would be as follows:

$$F_x = k_{xx}x + k_{xy}y$$

$$F_y = -k_{yx}x + k_{yy}y$$



where x and y are shaft displacements in the corresponding directions.

Rotor stability is jeopardized if either the coefficients k_{xx} or k_{yy} (radial stiffnesses) become too small, up to bluntly negative, or if the coefficients k_{xy} or $-k_{yx}$ (tangential or "cross coupled" stiffnesses) are too high.

The bearing/seal coefficients commonly used in rotor analyses are usually given in numerical/graphical or tabular form as functions of shaft eccentricity and/or Sommerfeld number, S. Usually the coefficients are not correlated with each other. Since the Sommerfeld number lumps the rotative speed (ω) and shaft radial load (W) in the quotient, the assumption is made that a proportional increase of ω and W will not modify fluid dynamic forces. For unloaded shafts ($W \approx 0$), $S \approx \infty$ and this important-for-stability case is usually not considered at all. The Sommerfeld number is often "modified" by some geometric multipliers, such as bearing length-to-diameter ratios or constant numbers (to match the dimensions of individual variables, fluid dynamic viscosity in the first place), but this does not improve the foggy picture of what the fluid dynamic forces in bearings and seals really represent and how they affect rotor stability.

Subsequent to the excellent work of Reynolds and Sommerfeld, a series of most unfortunate mistakes and bad assumptions were made, severly limiting and misdirecting rotor dynamics across half a century. Once the first misdirection occurred, a series of others followed as a result. In future articles these errors will be presented and corrected.

Interpretation of the physical phenomena occurring in unloaded and lightly loaded rotor/bearing/seal systems becomes easy and understandable if fluid circumferential flow is considered (Figure 1). Due to shaft rotation, fluid in the bearing/seal clearance undergoes rotative motion. Figure 1 presents a fluid velocity diagram. For steady-state conditions, the fluid layer next to the shaft rotates with circular speed ω; the layer next to the bearing (or seal) wall has zero velocity. The fluid average circular speed is approximately $\omega/2$. Actually, it is seldom equal to this well-known "half-speed" value. It varies with bearing/seal geometry, surface roughness, axial and secondary flow losses, and, above all, shaft eccentricity. We introduce, therefore, a coefficient λ, called the *fluid average circumferential velocity ratio.* This represents the fluid average circular speed as $\lambda\omega$ (instead of the commonly used constant $\omega/2$). The fluid average circumferential velocity ratio becomes the key factor in unloaded and lightly loaded rotor/bearing/seal dynamic models. It is easy to use, easy to interpret, and experimental as well as field results confirm its adequacy in the rotor models.

It is well known that rotor instabilities occur when full 360° circumferential flow is developed in bearings and/or seals.

Exactly the same holds true for the main flow in fluid-handling machines. However, the circumferential flow was never represented directly in fluid dynamic force models. This eventually created false illusions, one being that fluid pressure — not circumferential flow—is the most important factor.

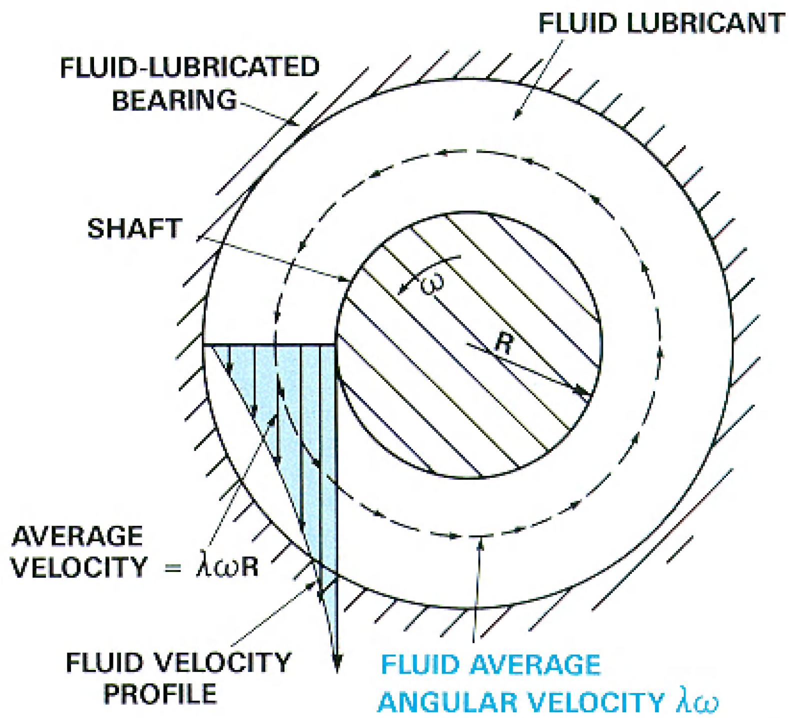
Fluid in dynamic motion is very much the same as solid bodies in motion. Fluid can be represented by similar mechanical parameters, such as stiffness, damping, and mass (inertia). The key point here is that due to shaft rotation the fluid undergoes rotative motion, and the averaged fluid dynamic forces — radial stiffness, radial damping, and fluid inertia — are rotating at the average rate $\lambda\omega$.

To make the story short, here are the values of the stiffness matrix coefficients (1) for the unloaded (concentric) shaft:

$$\begin{bmatrix} K-M_{fl}\lambda^2\omega^2 & D\lambda\omega \\ -D\lambda\omega & K-M_{fl}\lambda^2\omega^2 \end{bmatrix} \qquad (2)$$

where K is the fluid radial stiffness coefficient, D is fluid radial damping and M_{fl} is fluid inertia. Now it is easily seen that the radial stiffness can become negative (due to high centripetal fluid inertia). It is also evident that the "cross-coupled stiffness" is generated by fluid relative velocity correlated with damping. That is why the "cross-coupled stiffness" becomes proportional to the radial damping. It is clear, therefore, that any increase of fluid damping would not improve stability. The "cross-coupled stiffness" is also proportional to the average velocity ratio λ, and here it represents the major factor for stability control: A decrease of λ directly improves stability! This can be achieved by increasing shaft eccentricity (λ is a decreasing function of shaft eccentricity reaching zero at a certain "critical" value of eccentricity — at this "critical" value the periodic, fully developed circumferential flow disappears) or by introducing to the bearings (and especially to seals) a circumferential flow in the direction opposite to rotation. The latter is known as the anti-swirl technique.

From the stiffness matrix (2), it is also evident that rotor stability can be enhanced if fluid radial stiffness K is high. Higher fluid radial stiffness can be achieved by increasing fluid pressure. This is successfully accomplished by simple hydrostatic bearings. ■



Concentric shaft rotating inside a cylindrical bearing or seal: Fluid average angular circumferential velocity $\lambda\omega$.

Bently Rotor Dynamics Research Corporation awarded NASA contract

NASA has awarded a contract to Bently Rotor Dynamics Research Corporation (BRDRC) to assist in the development of the fuel turbo pumps for future space shuttle engines.

Don Bently said that he is extremely pleased to win this contract, not because it is the first government bid attempted, but because it is in a field where both he and Dr. Agnes Muszynska (Senior Research Scientist with BRDRC) have done extensive prior research.

Dr. Muszynska will be the principal researcher and Don Bently co-researcher. Wes Franklin will be the software design engineer, Lori Kingsley the metallurgical consulting engineer and Art Curry, the laboratory technician, will be running test models.

The bid was made over one year ago, but the award was delayed for months because of the Challenger accident in which 7 astronauts lost their lives. This research is on the shuttle's liquid fuel engines, and has nothing to do with the accident which involved the solid propellant rockets.

The contract was won over several major companies and university research groups that do research for the aerospace industry.

Dr. Muszynska is a native of Warsaw, Poland. She received her Bachelor of Science and Master of Science degrees in Mechanical Engineering from the Technical University of Warsaw and a doctorate in technical sciences from the Polish Academy of Sciences.

She has been Senior Research Scientist at Bently Nevada since 1981, conducting research on rotating machine dynamics and participating as an instructor in Bently Nevada's customer training seminars. Dr. Muszynska has authored more than 100 technical papers on mechanical vibration theory and machine dynamics. ■